

TEXTURE SYNTHESIS FOR REPAIRING DAMAGED IMAGES

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FIELD OF INVENTION

[0001] This invention relates to software for image inpainting and texture synthesis.

DESCRIPTION OF RELATED ART

[0002] Damaged images can be repaired by professional artists using a technique called inpainting. Various software inpainting techniques have been developed to undetectably repair images like professional artists. Bertalmio et al. proposes a method based on information propagation. M. Bertalmio, G. Sapiro, V. Caselles, and C. Ballester, "Image Inpainting," Computer Graphics, Proceedings of SIGGRAPH, pp. 417-424, New Orleans, July 2000. It takes the known gray values of the points in the boundary of the damaged areas and propagates these gray values to the damaged area along the direction which has a small gradient. Chan et al. proposes a method that repairs image by solving the Partial Differential Equation (PDE). T. Chan, A. Marquina, and P. Mulet, "High-Order Total Variation-Based Image Restoration," SIAM Journal on Scientific Computing, pp. 503-516, Vol. 22, No. 2, 2000.

[0003] Many damaged images look fine after being repaired by the aforementioned inpainting methods. However, these methods have a common shortcoming: all of them cannot retrieve the texture information of the image. This shortcoming is not very obvious when only a small area of the image is damaged. When a large area of the image is damaged, the result looks blurry without texture information and can be easily detected by the human eyes.

[0004] Texture synthesis methods can also repair damaged images, such as non-parametric sampling that creates texture using a Markov random fields (MRF) model. In the MRF model, the conditional Probability Distribution Function (PDF) of a point is calculated by using the

neighbor points. The information of the damaged point is duplicated from a point which has the same conditional probability distribution. Efros et al. proposes a method that duplicates the information point by point. A. Efros and T. Leung, "Textutre Synthesis by Non-parametric Sampling," In Proceedings of International Conference on Computer Vision, 1999. Liang et al. proposes a method based on patches (i.e., blocks). L. Liang, CE Liu, Y. Xu, B. Guo, and H. Shum, "Real-Time Texture Synthesis by Patch-Based Sampling," Microsoft Research Technical Report MSR-TR-2001-40, March 2001.

[0005] The aforementioned texture synthesis methods can repair pure texture images well. However, the actual images in practice (such as natural images) often do not have features with repetitive texture. Furthermore, the texture features of these images are complicated by their environment such as lighting. Repairing images using the aforementioned texture synthesis methods without addressing these problems will not produce a satisfactory result.

[0006] Thus, what is needed is a method for repairing damaged images that addresses the shortcomings of the conventional inpainting and texture synthesis methods.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figs. 1A, 1B, 2A, 2B, and 2C illustrate a conventional patch-based sampling algorithm.

[0008] Fig. 3 illustrates a method for filling an image in one embodiment of the invention.

[0009] Figs. 4 and 6 illustrate the filling of an area in an image with a sample patch in one embodiment of the invention.

[0010] Fig. 5 illustrates a boundary zone of a patch divided into individual boundary areas in one embodiment of the invention.

[0011] Figs. 7A, 7B, and 7C illustrate the improvement of the method of Fig. 3 over the conventional patch-based sampling algorithm.

[0012] Use of the same reference numbers in different figures indicates similar or identical elements.

SUMMARY

[0013] In one embodiment of the invention, a method for generating texture includes (1) selecting a target patch to be filled in an image, (2) selecting a sample patch as a candidate for filling the target patch, (3) determining a first difference between a first area surrounding the target patch and a corresponding first area surrounding the sample patch, and a second difference between a second area surrounding the target patch and a corresponding second area surrounding the sample patch, (4) multiplying a larger of the first difference and the second difference with a first weight factor, and a smaller of the first difference and the second difference with a second weight factor, and (5) summing the weighted first difference and the weighted second difference as a distance between the target patch and the sample patch.

DETAILED DESCRIPTION

Problems of a conventional patched-based sampling algorithm

[0014] Liang et al. discloses a patch-based sampling algorithm for synthesizing textures from a sample. This sampling algorithm is hereafter explained in reference to Fig. 1A where an image 2 has a target area 4 to be filled with textures from a sample texture 6. Target area 4 is divided into target patches B_k having a patch size of w by w (only one is labeled for clarity), where k is a variable. If the width or the height of target area 4 is not a multiple of w , the size of the last row and the last column of target patches is defined as:

$$w * w_1, w_2 * w, \quad (1)$$

$$w_1 = W \bmod w, \quad w_2 = H \bmod w, \quad (2)$$

where W and H express the width and height, respectively, and \bmod is the function that calculates the residual of W or H divided by w .

[0015] Each target patch B_k includes a boundary zone E_{B_k} having a width w_E surrounding the target patch. Boundary zone E_{B_k} includes known texture from image 2 and derived texture from filling in other surrounding target patches with textures from sample texture 6.

[0016] Sample texture 6 is divided into sample patches $B_{(x,y)}$ (only one is labeled for clarity), where (x,y) denotes the left-lowest point of the sample patch. Sample patches $B_{(x,y)}$ and target patches B_k have the same size. Each sample patch $B_{(x,y)}$ includes a boundary zone $E_{B_{(x,y)}}$ surrounding the sample patch.

[0017] The corresponding points in boundary zones $E_{B_{(x,y)}}$ and E_{B_k} are compared to determine if a sample patch $B_{(x,y)}$ matches a target patch B_k . If the distance (i.e., the difference) between the sample patch $B_{(x,y)}$ and the target patch B_k is less than a prescribed threshold, then that sample patch $B_{(x,y)}$ is placed in a set ψ_B . The definition of set ψ_B is:

$$\Psi_B = \{ B_{(x,y)} \mid d(E_{B_{(x,y)}}, E_{B_k}) < d_{max} \}, \quad (3)$$

where d is the distance between boundary zones $E_{B_{(x,y)}}$ and E_{B_k} of sample patch $B_{(x,y)}$ and target patch B_k , respectively, and d_{max} is the prescribed threshold. The definition of distance d between boundary zones E_{B_k} and $E_{B_{(x,y)}}$ is:

$$d(E_{B_k}, E_{B_{(x,y)}}) = \left[\frac{1}{A} \sum_{i=1}^A (p_{B_k}^i - p_{out}^i)^2 \right]^{1/2}, \quad (4)$$

where A is the number of corresponding points in boundary zones $E_{B_{(x,y)}}$ and E_{B_k} , and $p_{B_k}^i$ and p_{out}^i denote the corresponding gray values of the corresponding points.

[0018] After all the sample patches $B_{(x,y)}$ in sample texture 6 are compared with a target patch B_k , then a sample patch $B_{(x,y)}$ is randomly selected from set ψ_B and used to fill target patch B_k . If set ψ_B is empty, then a sample patch $B_{(x,y)}$ with the smallest distance is selected to fill target patch B_k . This process is repeated for each target patch B_k in target area 4 of image 2.

[0019] After filling in one target patch, the texture of that target patch becomes part of the known boundary zones of adjacent target patches. For example in Fig. 1B, a left area of a

boundary zone $E_{B_{k+1}}$ from a target patch B_{k+1} becomes a known right area of a boundary zone $E_{B_{k+2}}$ from a target patch B_{k+2} . After sample patches fill in the target patches, the overlapping areas of their boundary zones are blended.

[0020] Fig. 2A illustrates a target area 4 divided into nine target patches. As described above, the target patches can be filled one by one. Fig. 2B illustrates one order in which the target patches are filled in row by row. Fig. 2C illustrates one order in which the target patches are filled by an inward spiral order.

[0021] One disadvantage of Liang et al. is that formula 4 applies the same weight to all the areas that make up the boundary zones. For example, assuming a target patch having a boundary zone with known left and lower areas is compared with a sample patch having a boundary zone with a very similar or the same left area. The distance calculated may be smaller than the prescribed threshold because of the similarity between the left areas around the target and the sample patches even though the lower areas around the target and the sample patches are very different. When such a sample patch is used to fill the target patch, the lower portion of the sample patch may be greatly visible in the image. Furthermore, the selection of this sample patch will affect the subsequent target patches that are filled as the dissimilarity is propagated through subsequent matching operations.

[0022] Another disadvantage of Liang et al. is that it fails to compensate for asymmetrical lighting. Asymmetrical lighting in an image will give different gray values to the same texture. This makes it difficult to fill a target area with the proper texture because areas with similar gray values may have different textures while areas with the same texture may have different gray values. When a sample patch is pasted directly onto a target patch, then the sample patch may be visible in the image.

Improvement to the patched-based sampling algorithm

[0023] Fig. 3 illustrates a method 10 for filling a target area 102 (Fig. 4) in an image 104 (Fig. 4) with textures from a sample texture 106 (Fig. 4) in one embodiment of the invention. Target area 102 may be a damaged area that needs to be repaired while sample area 106 may be any undamaged area outside of target area 102 in image 104. Alternatively, sample area 106 can be

another image or a group of sample patches. Method 10 can be implemented with software on a computer or any equivalents thereof.

[0024] In step 12, the computer optionally converts image 104 from a color image into a gray scale image. The computer can convert the color values into gray scale values as follows:

$$I(x, y) = \frac{R(x, y) + G(x, y) + B(x, y)}{3}, \quad (5)$$

where I is the gray value of a point, and R, G, B are the color values of the point. This step may help to speed up the processing later described. Step 12 can be skipped if image 104 is a gray scale image from the start.

[0025] In step 14, the computer receives a target area 102 to be filled. Typically, target area 102 is designated by a user after the user visually inspects image 104.

[0026] In step 16, the computer divides target area 102 into target patches B_k with associated boundary zones E_{B_k} .

[0027] In step 18, the computer divides sample area 106 into target patches $B_{(x,y)}$ with associated boundary zones $E_{B_{(x,y)}}$.

[0028] In step 20, the computer selects a target patch B_k from target area 102 to be matched with a sample patch. In one embodiment, the computer selects the target patch in an inward spiral order.

[0029] In step 22, the computer selects a sample patch $B_{(x,y)}$ from sample area 106 to be compared with target patch B_k .

[0030] In steps 24 and 26, the computer determines the distance between the current target patch B_k and the current sample patch $B_{(x,y)}$. Specifically, in step 24, the computer determines the difference between the corresponding points in boundary zones E_{B_k} and $E_{B_{(x,y)}}$. Unlike Liang et

al., the computer divides the boundary zones into boundary areas and then determine the differences between the corresponding boundary areas as follows:

$$d_n = \left[\frac{1}{A_n} \sum_{i=1}^{A_n} (p_{B_i}^i - p_{B_{(x,y)}}^i)^2 \right]^{1/2}, \quad 2 \leq n \leq 4, \quad (6)$$

where d_n is the difference of the n th pair of corresponding boundary areas in boundary zones E_{B_k} and $E_{B_{(x,y)}}$, A_n is the number of corresponding points in the n th pair of corresponding boundary areas, and $p_{B_k}^i$ and $p_{B_{(x,y)}}^i$ denote the corresponding gray values of the corresponding points. In one embodiment, the computer divides each boundary zone into a top boundary area B_{top} , a left boundary area B_{left} , a bottom boundary area B_{bot} , and a right boundary area B_{right} as shown in Fig. 5. Note that the four corners are part of two boundary areas and will be calculated twice in equation 6.

[0031] In step 26, the computer weighs the differences of the corresponding areas and then sums the weighted differences as follows:

$$d = \sum_{i=1}^n \alpha_i d_i, \quad 0 < \alpha_i \leq 1, \quad (7)$$

where d is the distance between target patch B_k and sample patch $B_{(x,y)}$, d_i is the difference of the i th pair of corresponding boundary areas in a descending sequence, α_i is the weight given to difference d_i , and n is the total number of corresponding boundary areas. The value of α_i is determined by boundary width w_E and patch size w (where patch size w is typically determined by the size of the smallest repeated unit of texture known as textone, and w_E is typically $(\frac{1}{5} \sim \frac{1}{4}) w$). In one embodiment, value of α_i is determined as follows:

$$\alpha_i = \frac{1}{sequence(d_i)}, \quad (8)$$

where the *sequence* is the descending sequence of the distances from the biggest to the smallest. Equation 8 thus gives different weights to different boundary areas, and the boundary area with the biggest distance has the weight 1.

[0032] In step 28, the computer determines if the distance between the current target patch B_k and the current sample patch $B_{(x,y)}$ is less than a prescribed threshold. If so, then step 28 is followed by step 30. Otherwise, step 28 is followed by step 32.

[0033] In step 30, the computer puts the current sample patch $B_{(x,y)}$ in a set ψ_B , which contains all the sample patches that can be used to fill target patch B_k .

[0034] In step 32, the computer determines if all the orientations of the current sample patch $B_{(x,y)}$ have been compared with the current target patch B_k . This is because image 102 may have symmetrical areas, caused by reflection or other reasons, that can provide a good match for a target patch. Thus, different orientations of the current sample patch B_k are also compared for an acceptable match with the current target patch B_k . In one embodiment, the current sample patch $B_{(x,y)}$ is orthogonally rotated three times from its original orientation to see if any of the other orientations provide an acceptable match with the current target patch B_k . If all the orientations of the current sample patch $B_{(x,y)}$ have been tried, then step 32 is followed by step 36. Otherwise step 32 is followed by step 34.

[0035] In step 34, the computer rotates the current sample patch $B_{(x,y)}$. Step 34 is followed by step 24 and the newly rotated sample patch $B_{(x,y)}$ is compared with the current target patch B_k . Method 10 repeats this loop until all the orientations of the current sample patch $B_{(x,y)}$ have been compared to the current target patch B_k .

[0036] In step 36, the computer determines if the last sample patch $B_{(x,y)}$ in sample area 106 has been compared with the current target patch B_k . If so, then step 36 is followed by 38.

Otherwise step 36 is followed by step 22 and another sample patch $B_{(x,y)}$ is selected. Method 10

thus repeats this loop until all the sample patches $B_{(x,y)}$ in sample area 106 have been compared to the current target patch B_k .

[0037] In step 38, the computer randomly selects a sample patch $B_{(x,y)}$ from set ψ_B to fill the current target patch B_k . If set ψ_B is empty, then the computer selects the sample patch $B_{(x,y)}$ with the smallest distance to fill the current target patch B_k .

[0038] In step 40, the computer adjusts the gray values of sample block $B_{(x,y)}$ to make them look natural with the boundary values of the current target patch B_k and at the same time keep their texture features. Assume an image g is the selected sample patch and an image f is the boundary around the current target patch. It is desired to generate a new sample patch u that has the same texture features as selected sample patch g (i.e., have the same color gradient) and has the same color at its boundary f .

[0039] In order to keep the gradient of the selected sample patch g , the new sample patch u should satisfy the functions:

$$\begin{aligned}\frac{\partial u}{\partial x} &= \frac{\partial g}{\partial x} \\ \frac{\partial u}{\partial y} &= \frac{\partial g}{\partial y}\end{aligned}\tag{9}$$

where $\frac{\partial u}{\partial x}$ is the gradient of the new sample patch u in x direction at point (x, y) , $\frac{\partial u}{\partial y}$ is the gradient of the new sample patch u in y direction at point (x, y) , $\frac{\partial g}{\partial x}$ is the gradient of the selected sample patch g in x direction at point (x, y) , and $\frac{\partial g}{\partial y}$ is the gradient of the selected sample patch g in y direction at point (x, y) . Equation 9 can be rewritten as:

$$\begin{aligned} \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x}\right)^2 &= 0 \\ \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y}\right)^2 &= 0 \end{aligned} \Leftrightarrow \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y}\right)^2 = 0. \quad (10)$$

[0040] In order to make the new sample patch u have the same color at its boundary area f , the new sample patch u should satisfy the function:

$$u = f \quad (11)$$

Equation 11 can be rewritten as:

$$u = f \Leftrightarrow (u - f) = 0 \Leftrightarrow (u - f)^2 = 0. \quad (12)$$

Equations 10 and 12 can be combined into a single equation as follows:

$$\begin{aligned} (u - f)^2 &= 0 \\ \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y}\right)^2 &= 0 \Leftrightarrow (u - f)^2 + \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y}\right)^2 = 0, \end{aligned} \quad (13)$$

In other words, the new sample patch u should satisfy the equation 13 at point (x, y) . Satisfying these conditions for the entire new sample patch u , equation 13 is rewritten as:

$$\sum_{x \in \Omega} \sum_{y \in \Omega} \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y} \right)^2 + (u - f)^2 = 0. \quad (14)$$

where Ω is the area to be pasted with the new sample patch u . If equation 14 is written in continuous form, it becomes:

$$\int_{\Omega} \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y} \right)^2 + (u - f)^2 dx dy = 0. \quad (15)$$

As there is no solution of the new sample patch u that satisfies equation 15, the closest solution for the new sample patch u is determined by defining a function $J(u)$ as follows:

$$J(u) = \int_{\Omega} \left(\frac{\partial u}{\partial x} - \frac{\partial g}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial y} - \frac{\partial g}{\partial y} \right)^2 dx dy + \lambda \int_{\Omega} (u - f)^2 dx dy, \quad (16)$$

where λ is the weight given between satisfying the boundary condition against satisfying the gradient condition, and $d(x,y)$ is $dx dy$. Conventional minimizing methods, such as the Steepest Descent and Iteration, can be used to minimize function $J(u)$.

[0041] In step 42, the computer fills the current target patch B_k with the adjusted sample patch $B_{(x,y)}$. Unlike Liang et al., where the boundary zone of the sample patch is also filled in to overlap with the known areas outside of the target patch and the areas derived from the filling of other target patches, the computer only fills in the selected sample patch $B_{(x,y)}$ without its boundary zone $E_{B_{(x,y)}}$ into the current target patch B_k . As shown in Fig. 6, any area within the selected sample patch $B_{(x,y)}$ can become the boundary zone of another target patch B_{k+1} to be filled. Specifically, part of sample patch $B_{(x,y)}$ becomes a left area B_{left} of boundary zone $E_{B_{k+1}}$ of target batch B_{k+1} .

[0042] In step 44, the computer determines if the current target patch B_k is the last target patch in target area 102. If so, then step 44 is followed by step 46. Otherwise step 44 is followed by step 20 and another target patch B_k is selected. Method 10 thus repeats this loop until all the target patches B_k in target area 102 have been filled.

[0043] In step 46, the computer optionally converts image 102 from a gray scale image into a color image. In one embodiment, the computer imposes the color characteristics of the original color image 102 onto the gray scale image 102 using the method disclosed by Reinhard et al. E. Reinhard, M. Ashikhmin, B. Gooch, P. Shirley, "Color Transfer between Images," IEEE Computer Graphics and Applications, Vol. 21, No. 5, September/October 2001.

[0044] As described above, method 10 provides many improvements over the conventional patched-based sampling algorithm disclosed by Liang et al. First, method 10 weighs the different areas of the boundary zones differently when calculating the distance between a sample patch and a target patch. Second, method 10 adjusts the gray values of the sample patch to better match the target patch. Third, method 10 compares the sample patch at various orientations to

better match the target patch. Fourth, method 10 converts color images to gray scale images to improve processing speed.

[0045] Fig. 7A illustrates an image 202 having a target area 204 to be filled with texture from a sample area within image 202 but outside of target area 204. Fig. 7B illustrates image 202 after it has been filled by the conventional patched-based sampling algorithm disclosed by Liang et al. A patch size of 20 * 20 pixels and a boundary width of 4 pixels were used. A 600 * 400 pixels image 202 and a 100 * 40 pixels target area 204 were used. As the figure shows, the filled area is still visible to the human eyes. Fig. 7C illustrates image 202 after it has been filled by method 10 (Fig. 3) using the above parameters in one embodiment of the invention. As the figure shows, the filled area is not visible to the human eyes.

[0046] Various other adaptations and combinations of features of the embodiments disclosed are within the scope of the invention. Numerous embodiments are encompassed by the following claims.